Swansea Bay tidal powerplant: Bi-directional bulb pump-turbine with variable speed

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The present paper describes the experiences gained and the challenges encountered by Andritz Hydro in the last years during the development of the hydro-mechanic equipment for the Swansea Bay Tidal Power Plant project. With its triple regulated "Bi directional bulb pump turbines" it is the first tidal power plant in the world which will have a nominal power above 320 MW.

An important goal of the Swansea Bay Tidal project was the maximization of the Annual Energy Production (AEP). Andritz Hydro developed a new concept for a "Bi directional bulb pump turbine", with variable speed, turnable runner blades and guide vanes. The sixteen turbines are able to produce energy at incoming and outgoing tides. The triple regulated turbines allow very efficient power generation and the possibility of pumping, gives an additional energy increase. Good performance for turbining and pumping modes in both directions could be confirmed on the hydraulic test rig.

In order to maximize the AEP, in addition to the hydraulic development a software was developed that calculates the AEP taking into account all different operating modes i.e. turbining, pumping and sluicing in both directions. The AEP software in combination with advanced optimization algorithms is used to maximize the net AEP by optimizing the tidal plant operation through the year. The AEP optimizer will as well be used to run the control system of the power plant with optimum performance during operation.

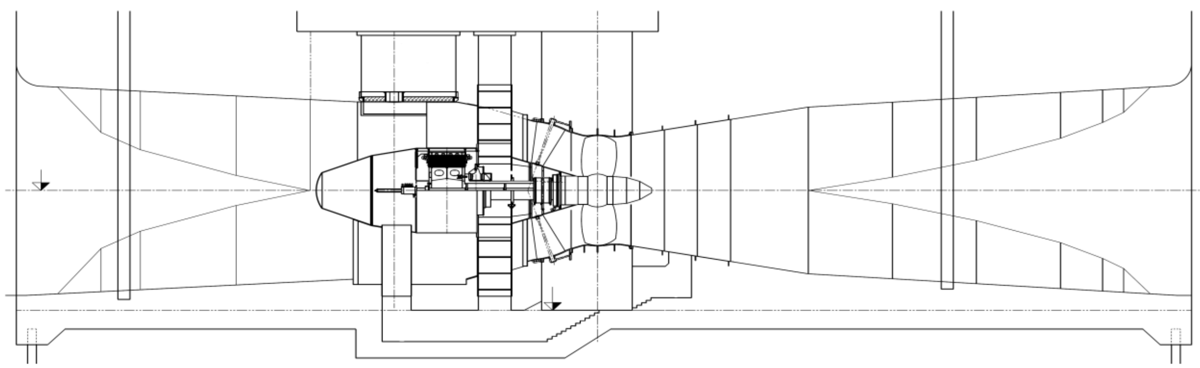

Fig. 1. Cross section through the "Bi directional bulb pump turbines".

The concept of a triple regulated "Bi directional bulb pump turbine" with its AEP optimization scheme will be presented in the paper. The execution phase of the power plant is currently ongoing and commissioning is planned for the year 2019.

1. Location/Geography

The project, developed by TLSB (Tidal Lagoon Swansea Bay o), is located in Swansea Bay in Great Britain. The figure shows the dam, where the power house is located at the south west. The position of the powerhouse and dam was verified using a combination site investigation results and modelling applications to investigate water quality, effects on navigation and hydrodynamic effects. Further physical model testing was undertaken by HR Wallingford in the UK and Deltares in the Netherlands both independent institutes for applied research in the field of water and subsurface. The intake is facing the lagoon in order to produce the optimal net annual energy production of ~540GWH.

Swansea Bay Tidal Power plant is the first of six planned tidal power plants in the UK.

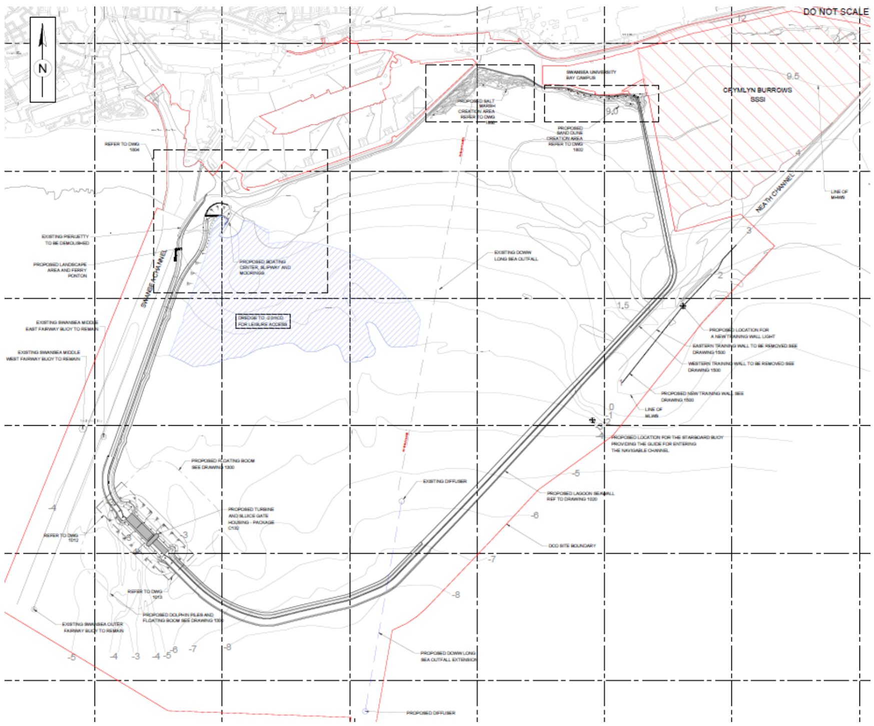

Fig. 2. Marine works plan with wall sections.

2. Background

In the year 2012 TLSB started with investigations to build a tidal lagoon to generate renewable energy in Swansea Bay. So TLSB set up a competition between several contractors to check the feasibility of the project. During this competition Andritz Hydro set up a model test to do extensive investigations if it is possible to execute a project with these special requirements.

Andritz Hydro is able to refer to more than 170 years of experience in turbines and especially in bulb turbines. In reference to Sihwa power plant in South Korea, which the currently operating largest Tidal Plant in the world equipped also by Andritz Hydro, 2 phases of the model test were planned. First to check the feasibility of the project by checking different concepts and in the second phase improvements were done based on the well-chosen concept to ensure the maximum annual energy production.

The model test started at the end of 2013 in combination with “Computational fluid dynamics” (CFD) and an annual energy production optimization. With the physical model of Sihwa a triple regulated concept was developed by applying a well analysed operating scheme to produce maximum annual energy. At the early stage of the tests it was soon proven that without pumping the project will not be feasible. At the second phase the model of Sihwa was improved based of the results of CFD. Efficiency, cavitation and special tests were done to provide a good foundation for the bid and TLSB nominated Andritz Hydro as supplier.

2. Operating scheme

The following graph shows the operating scheme of Swansea Bay tidal power plant. Over a tide period (12 hours) 8 operating modes will be driven.

Starting with the lowest sea level, water is pumped (PMR) in opposite direction through the turbine. Idle time (IT I) begins when a balance between sea and basin level occurs in order to build up a head for turbining in reverse mode (TMR). This mode ends with sluicing (S I) until sea and basin level are equal again. Next water is pumped (PM) in normal direction through the turbine. Idle time (IT II) begins when a balance between sea and basin level occurs in order to build up a head for turbining (TM) in normal mode. This mode ends again with sluicing (S II) until sea and basin level are equal again.

The change in modes is triggered by the AEP-optimizer to get the maximum power output which will be explained in detail at chapter 5.

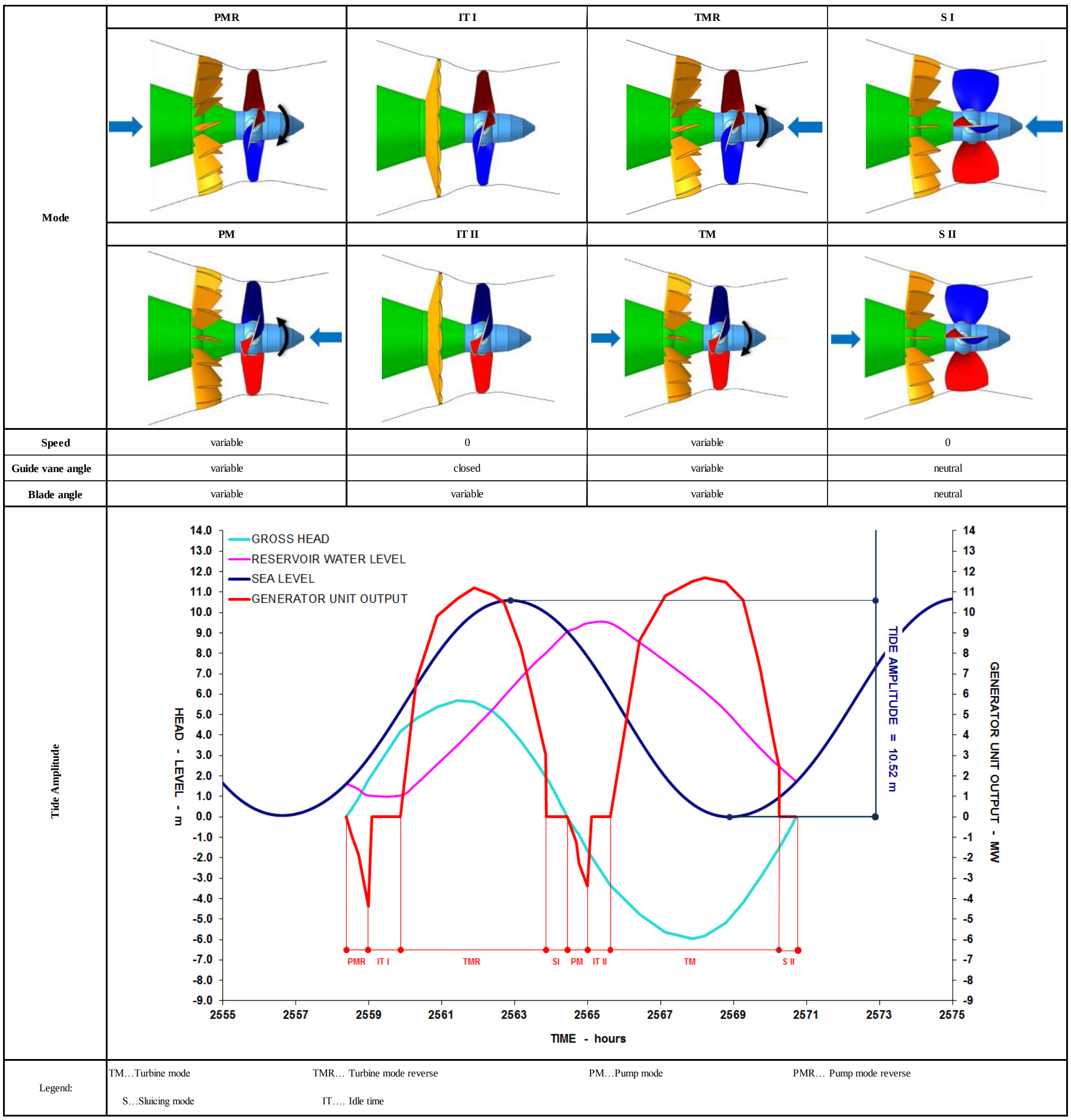

Fig. 3. Operating scheme of the "Bi directional bulb pump turbines".

3. Main dimensions of units

The following table shows all important data of Swansea Bay Tidal Power plant.

		TM	PM	TMR	PMR
Direction of rotation	-	clockwise	Counter-clockwise	counter-clockwise	clockwise
Speed	rpm	20 - 80	10 - 70	30 - 70	10 - 60
Maximum net head	m	7	3	6	3
Number of guide vanes	-	16	16	16	16
Maximum hydraulic power output	MW	22.0	10.0	20.0	6
Runner diameter	m	7.35	7.35	7.35	7.35
Maximum discharge	m^3/s	400	300	400	300

4. Hydraulic development

The request for the Swansea Bay turbine concept was the development of a workable and powerful solution. Feasible solutions were subjected to a detailed CFD analysis regarding efficiency and cavitation behaviour of the turbine.

The hydraulic development of axial turbines such as Kaplan, Bulb and Matrix turbines is based on comprehensive CFD simulations. CFD has become an essential tool for axial turbine development during the last decades. Its range of application reaches from feasibility studies and design optimization to advanced simulations of unsteady complex flow features. Hydraulic optimization flow simulations deliver the loading on structures for structural stress analysis (FEM). This combination of CFD and structural analysis enables a reliable lifetime prediction of hydraulic components.

Bulb turbines usually work in one flow direction, as it is for a river power plant. Due to the tide, the flow direction is changing and the power generation for Swansea has to work in both directions. After some AEP optimizations cycles, it turned out that the pump mode became a more and more important part to use the potential of the tidal energy.
During the CFD design process, the main focus was on the turbine operation in both directions. By changing and optimizing the runner blade geometry, the effects on all operation modes were checked. Therefor a CFD analysis was performed in different modes to see the influence of the several runner modifications.

Andritz Hydro typically performs CFD based optimization on three different levels of complexity.
Level 1: In a first step a preliminary design is developed on a coarse design level using a 3D-Euler solver. Target is an optimal runner outlet velocity profile in order to both minimize swirl and optimize the draft tube inflow on one hand and an optimized pressure field for cavitation prevention on the other hand by means of increasing the minimum pressure on the entire blade surfaces above vapour pressure. The disadvantage of the absence of friction and turbulence effects which are not modelled by the Euler equations are compensated by the delivery of a reliable prediction of the pressure distribution and flow angles within minutes.

Level 2: In a second step the most promising pre-optimized variants are checked using more detailed CFD simulations. 3D-Navier-Stokes simulations are carried out for the same set of operating points as in the first step. Contrary to Level 1 the flow simulations now include the gaps at the hub and at the blade tip as well as the guide vanes in order to simulate realistic runner inflow conditions. As in Navier-Stokes simulations friction and turbulence effects are taken into account, the runner efficiency can be used as additional objective to further reduce the set of promising variants, which then are usually passed to the 3rd optimization level. Figure 4 shows the flow behaviour of a 3D-Navier-Stokes simulation for finding the ideal Guide Vane angel for a specific operation in turbine reverse mode.

Level 3: In the third optimization step 3D-Navier Stokes simulations including the draft tube are carried out for a number of operating points on a propeller curve which is chosen firstly, to represent the most important operating conditions and secondly, to confirm the fulfilment of the performance guarantees.
Bulb turbines operate under almost optimal conditions in the entire operating range. Therefore, steady-state CFD is a reliable method for the design of double regulated turbines. Nevertheless, every CFD model has to be set up properly to achieve accurate and reliable solutions and the possible sources of error are manifold.

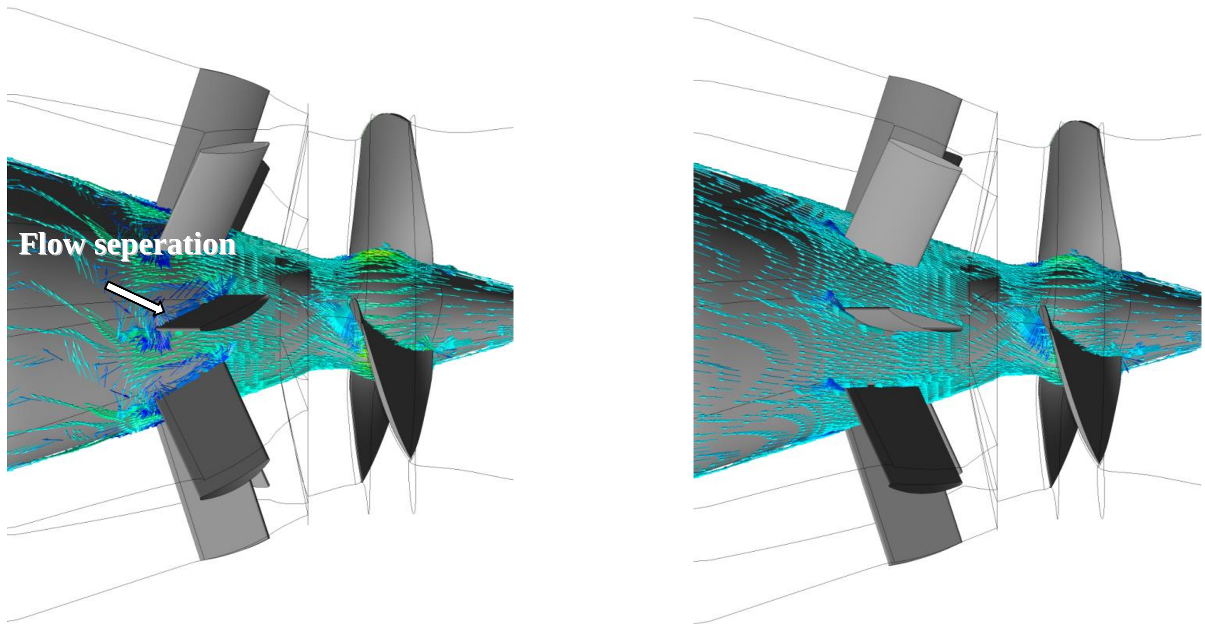

Fig. 4: Left picture: Guide Vanes are not aligned with the flow, this leads to flow separation and to high losses
Right picture: Optimal Guide Vane angle – flow aligned – high efficiency

The runner design for Swansea Bay is obtained by the normal AH design procedure. The final concept for Swansea Bay was achieved by using an evaluation procedure by means of CFD performance calculation in parallel with AEP optimisation. Consequently performance guarantees of Bulb turbines can be estimated on basis of thoroughly validated and carried out CFD simulations.

For Bulb turbines, which usually are characterized by relatively low head and high discharge, the most accurate way to determine the turbine efficiency is a fully homologous model test. While the measurement tolerance for efficiency at the test stand is approximately ±0.25%. A model test furthermore gives the possibility to investigate the cavitation behaviour of the turbine thoroughly and to measure additional values such as axial thrust and runner blade as well as guide vane torque.
While CFD is a very valuable tool for turbine design and the backbone of hydraulic water turbine development, a CFD based runner development of a Bulb turbine remains challenging and numerical flow simulations cannot serve the purpose of a proof of guarantee. This is a main reason for the need of model tests.

5. AEP

In order to maximize the Annual Energy Production (AEP), a tool was specifically developed by Andritz Hydro that calculates the AEP while simulating all the different operating modes. The AEP calculation tool in combination with an advanced optimization software (the EASY [1] software based on Evolutionary Algorithms) was used to maximize the AEP and optimize the tidal plant operation throughout the year. In Figure 4, the AEP optimization loop is presented with the coupling between the optimizer EASY and the AEP calculation tool. After defining the optimization design variables and constraints, the optimization searches the design space in order to provide the optimal solution that corresponds to the maximum net AEP and the optimal tidal plant operation. The design variables of the AEP optimization are the basin level path, the speed and the time step for each operating point and the start and stop head for each operating mode. The constraints of this optimization consist of maximum power and cavitation limitations for each operating point and basin level head limitations due to environmental reasons. The goal of the optimization is to define the optimal basin level path across the year by defining the optimal points of operation that respect the aforementioned constraints. The optimization searches over the four hill charts (each one for each operating mode) for the optimal operating points that maximize the AEP.

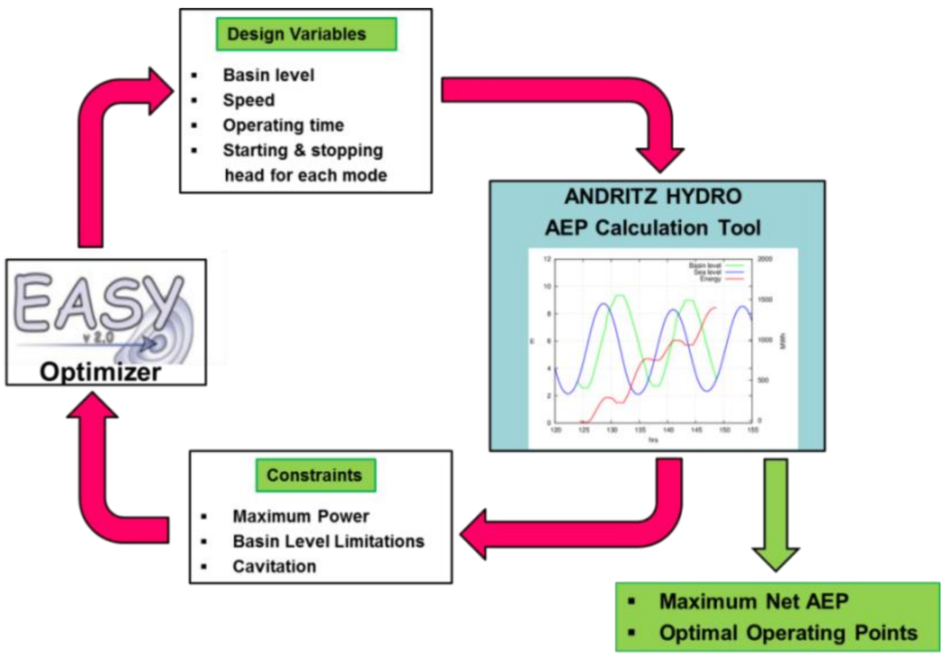

Figure 5: AEP Optimization Scheme based on the AEP calculation tool developed by Andritz Hydro and the EASY optimizer. The optimization is based on the definition of the optimization design variables and constraints and provides the maximum net AEP along with the optimal tidal plant operation throughout the year.

The AEP optimization along with hydraulic design development and model testing contributed to evaluate all different concepts not only from the hydraulic but also from the AEP point of view in order to define the optimal concept with the maximum AEP. AEP investigations on various optimization concepts such as of double/triple regulation, mitigation pumping (pumping until the maximum and minimum sea level of each tide), sluicing modes through gates and turbines and on intake and draft tube exit losses led to a significant increase of the AEP value. For example, mitigation pumping operation contributes with an increase on the AEP in comparison to the operation without pumping. Investigations have shown that pumping operation without having any basin level limitations can increase the AEP even more.

In order to minimize the risk of deviations of the AEP value, losses through the turbine and gate structures have to be determined and an optimal approach flow has to be investigated.

Apart from the design phase, the AEP optimization will be also used during operation of the power plant. In order to assure the optimal operation, an online optimization based on tide forecast will provide the optimal operating points (optimal guide vane angle, runner blade angle and speed) to the control system through the year.

6. Conclusion

After 2 years of investigation and development based on CFD analysis, AEP optimization and model testing it can be stated that a "Bi directional bulb pump turbine" with variable speed is the optimum concept using tidal energy to deliver clean, renewable and predictable power for over 155,000 homes for 120 years.

Swansea Bay Tidal Power plant will be the world's first, man-made, energy-generating lagoon, with a 320MW installed capacity and 14 hours of reliable generation every day. Commissioning and connecting to the national grid is planned in the year 2019. Based on the potential of tidal energy in the UK there is a goal to construct and operate further tidal lagoons to meet up to 8% of UK electricity demand.

Swansea Bay Tidal Lagoon Power plant will be the proof of concept for further tidal lagoons in UK and worldwide.

References

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The Authors

E. Kontoleontos graduated in Mechanical Engineering at the National Technical University of Athens (NTUA) in 2006 and did her doctoral studies from 2006 to 2012 in optimization methods and design optimization in Mechanical Engineering at NTUA. Between 2006 and 2013 she worked as a research engineer in the Geothermal Energy Department at the Centre for Renewable Energy Sources and Saving (CRES). Since 2013 she is working as a design engineer at Andritz Hydro Linz.

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M. Case is an environmental scientist with a background in renewable energy project development. For the last four years Mike has specialised in the global optimisation of tidal lagoon designs in order to maximise lagoon efficiency and energy yield whilst minimising impacts on fish. He has guided the development of the TLSB in-house energy modelling capability along with close collaboration with the world's leading turbine manufacturers to develop the state of the art turbine solution now selected for Swansea Bay. Prior to tidal lagoons Mike worked primarily in East Africa developing Tanzania's first commercial scale wind project with Wind EA Ltd which followed on from eight years working in senior management roles in international aid and development sector with Charles Kendall & Partners.